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# Helicopter Flights with Night-Vision Goggles – Human Factors Aspects

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## TABLE OF CONTENTS

|   | Page |
|---|------|
| SUMMARY .....   | 1    |
| I. INTRODUCTION .....   | 1    |
| II. NIGHT-VISION-GOGGLES SYSTEM CHARACTERISTICS .....         | 3    |
| A. Technical Description .....                                | 3    |
| B. Night-Vision-Goggles Installation .....                    | 4    |
| C. Light-Intensifier-Tube Parameters .....                    | 5    |
| D. Cockpit Lighting .....                                     | 7    |
| E. Superimposed Symbology .....                               | 8    |
| III. DAY VISION AND NIGHT VISION .....                        | 9    |
| A. The Human Eye .....  | 10   |
| B. Seeing by Day and by Night .....                           | 11   |
| C. The Use of Night Vision Goggles .....                      | 12   |
| D. Night Myopia and Instrument Myopia .....                   | 12   |
| IV. SEEING THROUGH NIGHT VISION GOGGLES .....                 | 13   |
| A. Field of View .....  | 13   |
| B. Binocular Vision .....                                     | 13   |
| C. Focal Distance .....                                       | 14   |
| D. Vision and Perception .....                                | 15   |
| E. Slope Estimation .....                                     | 16   |
| F. Instability of the World Image .....                       | 17   |
| G. Brightness and Dazzling .....                              | 18   |
| H. Monochrome Images .....                                    | 18   |
| I. Symbology in NVGs .....                                    | 18   |
| J. Visual Fatigue .....                                       | 20   |
| K. Individual Differences .....                               | 21   |
| V. LIGHT INTENSIFIERS VERSUS THERMAL IMAGING .....            | 22   |
| A. Thermal Imaging Systems .....                              | 22   |
| B. Characteristics of the Thermal Image .....                 | 23   |
| C. FLIR Helicopter Flying .....                               | 24   |
| D. Comparison of Thermal Imaging and Light Intensifiers ..... | 25   |
| E. Combining NVGs and FLIR .....                              | 28   |
| VI. CONCLUSIONS .....   | 30   |
| REFERENCES .....  | 31   |

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# HELICOPTER FLIGHTS WITH NIGHT-VISION GOGGLES— HUMAN FACTORS ASPECTS

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## SUMMARY

Night-vision goggles (NVGs) and, in particular, the advanced, helmet-mounted Aviators Night-Vision-Imaging System (ANVIS) allows helicopter pilots to perform low-level flight at night. It consists of light intensifier tubes which amplify low-intensity ambient illumination (star and moon light) and an optical system which together produce a bright image of the scene. However, these NVGs do not turn night into day, and, while they may often provide significant advantages over unaided night flight, they may also result in visual fatigue, high workload, and safety hazards. These problems reflect both system limitations and human-factors issues. A brief description of the technical characteristics of NVGs and of human night-vision capabilities is followed by a description and analysis of specific perceptual problems which occur with the use of NVGs in flight. Some of the issues addressed include: (1) limitations imposed by a restricted field of view; (2) problems related to binocular rivalry; (3) the consequences of inappropriate focusing of the eye; (4) the effects of ambient illumination levels and of various types of terrain on image quality; (5) difficulties in distance and slope estimation; (6) effects of dazzling; and (7) visual fatigue and superimposed symbology. These issues are described and analyzed in terms of their possible consequences on helicopter pilot performance. The additional influence of individual differences among pilots is emphasized. In the last section thermal imaging systems (forward looking infrared (FLIR)) are described briefly and compared to light intensifier systems (NVGs). Many of the phenomena which are described in the present report are not readily understood. More research is required to better understand the human-factors problems created by the use of NVGs and other night-vision aids, to enhance system design, and to improve training methods and simulation techniques.

## I. INTRODUCTION

Pilots of helicopters and other types of military aircraft rely heavily on visual information for navigation, obstacle avoidance, and target detection and acquisition. Hence, the ability to perform missions during the night (or other periods of reduced visibility) is severely restricted in comparison with operations in good visibility. Considering the tactical importance of night operations, considerable effort has been invested in the design and development of various visual aids. Some of the most important systems are:

1. Visible light sources— Search lights were used widely during World War II, particularly in defense missions, to aid in the detection of aircraft and other types of targets and are still used under some circumstances. Flares are widely used to illuminate wide areas for a limited period of time; a series of flares can be used to provide successive illuminations of an area. The use of flares may eliminate the

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chances of surprising the enemy, however, as they reveal both friends and foes, and destroy night-vision adaptation for a long period of time.

2. **Invisible light sources**– Sources of invisible electromagnetic radiation such as infrared radiation in the range of 0.7-1.2  $\mu\text{m}$ , may be used by operators who are equipped with appropriate devices. These consist of a filter which is installed on a light projector and allows only invisible infrared light to come through. Visual aids which are responsive at these particular wavelengths enable the user to see the illuminated area. The quality of visual information thus provided is generally inferior to visible light source in both intensity and range of illumination. In addition, the light may be detected by anyone who possesses proper viewing devices.

3. **Thermal imaging**– Forward Looking Infrared (FLIR) systems consist of detectors which are reactive to radiated heat (radiation in the far infrared, 3-5 or 8-14  $\mu\text{m}$ ), optical components, and signal processors which transform the signal into a visible display. The FLIR systems are in wide use for surveillance purposes, target detection and acquisition, helicopter flying, etc. Considerable effort has been invested in several countries to improve these systems and to increase the scope of their applicability.

Some of the advantages of thermal-imaging systems are:

- a. A world view can be obtained independent of visible light sources.
- b. Targets can be detected through smoke, dust, and camouflage.
- c. Hot targets may be detected from long distances.

Some of the disadvantages are:

- a. Technical complexity, heavy weight, large size, and high cost.
- b. The thermal image is significantly different from black and white video images, and thus, may be difficult to interpret.
- c. The image changes over time and its quality depends on weather and atmospheric conditions.

4. **Light intensification**– Light-intensifying systems are based on tubes which intensify light in the visual and the near infrared band (0.35-0.95  $\mu\text{m}$ ). Such systems are capable of creating a bright “window” in an otherwise dark environment. To do so, they depend on the existence of sufficient light in the scene. The signals received by a light-sensitive substance may be transformed into a video signal to create a “low-light-level television” or projected directly onto a miniature phosphor screen. The latter solution is implemented in night-vision goggles (NVGs). In recent years, NVGs underwent important technical improvements and gained an increasingly important role in the performance of night missions by rotary-wing and fixed-wing aircraft.

The use of NVGs in flight for helicopter and other aircraft flying, raises a series of human-factors questions regarding night vision, perceptual phenomena, safety, and training. This paper deals with the human-factors aspects of helicopter flight using NVGs. There is particular emphasis on the visual and perceptual encounters of skilled and novice operators. This report is partially based on a recent report on NVGs in helicopter operations performed by the Israel Air Force, which was written by the author in collaboration with Michael Wagner and Daniel Gopher (Brickner, Wagner, and Gopher, 1987).

## II. NIGHT-VISION-GOGGLES SYSTEM CHARACTERISTICS

### A. Technical Description

The basic structure of NVGs is quite simple.

1. A field lens (objective) concentrates incoming light rays onto an image intensifier tube (fig. 1).

2. The image intensifier tube consists of a photo cathode—a photo-sensitive substance that emits electrons when exposed to light in the visible or the near infrared band, and an electron multiplier (or microchannel plate), which multiplies the electrons thousands of times. By varying the voltage across the electron multiplier disc, the gain of the multiplier can be controlled.

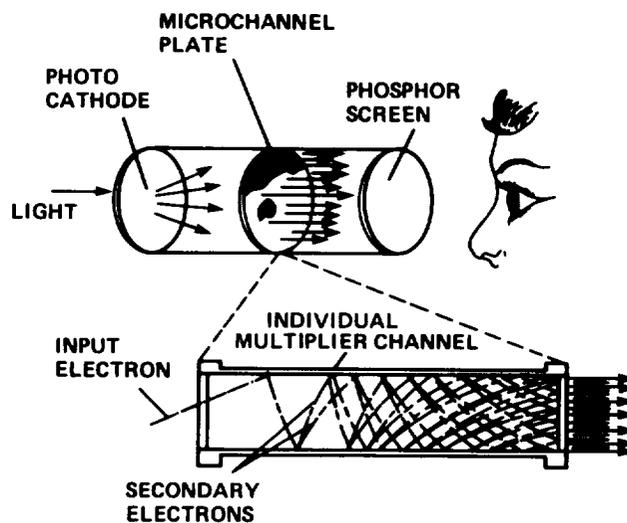


Figure 1.— Diagram of an intensifier tube.

Second- and third-generation tubes have an automatic gain control (AGC) system which controls the level of electron multiplying and protects it from excessive firing. The signals from the electron multiplier are transmitted through a bundle of fiber optics to a phosphor screen on which a visible image is created. The type of phosphor used determines the color of the image (usually green) and its persistence.

3. The collimating lens projects the image to optical infinity and focuses it onto the users' eyes. Alternatively, an indirect optical path may be devised, such that the image is viewed on a combining lens rather than directly from the phosphor screen.

4. Electrical power is supplied by batteries which are an integral part of the goggle housing in some systems and a separate box in others.

## B. Night-Vision-Goggles Installation

While first-generation light intensifier tubes were big and bulky, second and third generation tubes are sufficiently small that two of them can be used to provide a binocular head-mounted system. The AN/PVS-5 was the first NVGs system to be used for helicopter flying. It was originally designed for ground troops. It is worn with a face mask and harness which completely blocks peripheral vision. The more advanced AN/AVS-6 or ANVIS (Aviator Night-Vision Imaging System) goggles were designed specifically for helicopter pilots. These helmet mounted goggles are installed in front of the pilots' eyes. They are constructed so as to allow pilots to look around the goggles into the cockpit or to the outside world with their naked eyes (fig. 2).

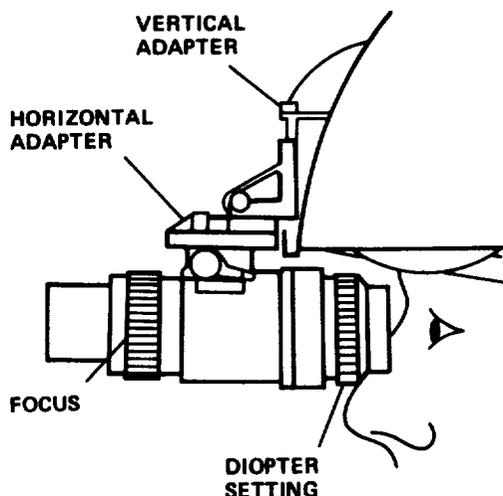


Figure 2.— ANVIS—Aviator Night-Vision Imaging System.

The goggles are installed on a quick-release mount which enables the user to lift them up away from the eyes or rapidly release them. The battery housing is separately installed on the back side of the helmet, counter balancing some of the weight of the goggles. The total weight of the system, including batteries, is approximately 850 grams.

The focal distance of the ANVIS may be set between 25 cm and infinity by moving the field lens. The ocular lens can be modified within the range of -6.0 to +2.0 diopters to compensate for short or far-sightedness (fig. 2).

Recently, a new type of helmet mounted goggles with an indirect optical path has been introduced. The image from a phosphor screen is projected onto a semi-transparent combiner lens which provides the user with an intensified world image and some see-through capabilities (fig. 3). These goggles were developed to be used in combination with other sources of visual information, such as head up displays (HUDs). One such system, "Cat's Eyes" (GEC Avionics) was tested by General Dynamics Corporation in conjunction with various navigation/attack FLIR pods (Bull, 1985). The "Cat's Eyes" weighs approximately 800 grams, however the battery housing is an integral part of the goggles, unlike the ANVIS. Hence, all of the weight is in the front of the helmet.

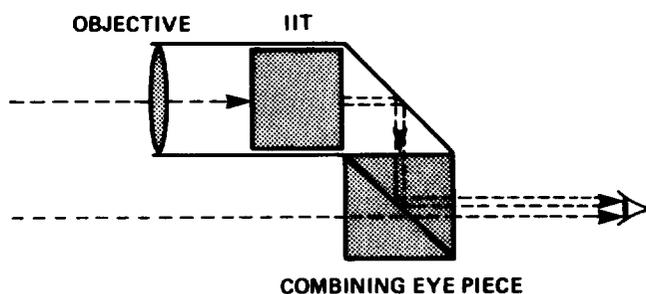


Figure 3.– Diagram of “Cat’s Eyes” NVGs with see-through capabilities.

### C. Light-Intensifier-Tube Parameters

In this paper some of the parameters which are most relevant to operators’ performance are discussed. A detailed technical description of the hardware can be found in Verona (1985). The data is based on Litton’s second-generation L-4261 tubes and on Varian VLIA-238 third-generation tubes. Specific features may be somewhat different in other brands.

1. **Resolution**– The resolving power of the goggles depends on the combined characteristics of all its components and is related to the contrast level of the scene. Maximal resolution is 25 pixels/mm at the center of the screen. Hence, the total maximum resolution of the round screen is approximately 450 pixels along its diameter. With 30% contrast, NVGs resolution drops to 16 pixels/mm or approximately 290 pixels along the diameter of the screen. Third-generation tubes may have up to 36 line-pairs/mm or a maximum resolution of 648 pixels along the diameter. In addition, they are more effective in low-brightness and low-contrast conditions.

Visual information thus provided may enable NVG users to estimate the probability of detecting or recognizing various targets. For example, let us assume that the width of a telephone pole is 30 cm. According to Johnson’s criteria (Johnson, 1958), 2 pixels are required to detect a target. However, due to the length of the target one may assume that 1 pixel may suffice. Given that the total field of view is 40° and there are approximately 650 pixels across the screen, one pixel extends 0.06° or 0.001 rad. The telephone pole will extend 0.001 mrad of visual angle from a distance of 300 m

$$\text{Distance} = 0.30 \text{ m} / 0.001 \text{ rad} = 300 \text{ m}$$

Thus, with the aid of an image intensifier, under optimal viewing conditions, a telephone pole may be detected from a distance of approximately 300 m.

In comparison, given sufficient contrast, the unaided eye has a resolving power of approximately 1 min of arc or 0.0003 rad (Snyder and Miller, 1977). Thus, under good day time visibility, the same telephone pole may be detected from a distance of approximately 1000 m

$$\text{Distance} = 0.30 \text{ m} / 0.0003 \text{ rad} = 1000 \text{ m}$$

In other words, the detection of small targets is limited by the resolution of the NVGs and is three to four times less than the maximum resolving power of the unaided eye during day time conditions.

2. **Image quality**— NVGs images are similar to those provided by a monochrome television screen. Image quality depends on the characteristics of the light intensifier tube, the optical system, atmospheric conditions, the nature of the scene, and ambient lighting. The maximum visual acuity of NVGs is often described in terms of visual acuity, and is supposedly 20/50 for second-generation and 20/40 for third-generation tubes (Tucker, 1984; Genco, 1985; Department of the Army, Field Manual 1983). This implies that a NVGs user should be capable of identifying from a distance of 20 ft, an object which a normal eye would identify from a distance of 40 ft. This acuity measure is ambiguous however, because as shown above, the resolving power of the unaided eye under good visibility, is three to four times higher than the resolution provided by third-generation NVGs. Thus the ability of NVGs to resolve fine detail is in fact smaller than 20/40.

3. **Ambient lighting**— The tube amplifies the light which is reflected from objects in the scene. On a bright night, the image will be bright and will consist of a wide range of gray shades. On a dark night the image will be darker and the range of gray shades reduced. Image brightness cannot be controlled by the user. Peak display luminance of second-generation NVGs is 0.3-0.7 foot lamberts (FL) and of third-generation NVGs 0.7-2.2 FL (Verona, 1985). The relatively low brightness level of the NVG display severely limits the number of distinct gray shades which can be displayed. Thus, brightness variability in the scene has to be mapped into a rather limited range of brightness in the display. The higher brightness and the improved range of third-generation tubes is one of its most important advantages over second-generation tubes.

4. **Atmospheric conditions**— Electromagnetic radiation within the sensitivity range of the tube (predominantly red and near infrared) is adversely effected by some of the factors to which the human eye is also sensitive, e.g., dust, moisture and haze. Thus, NVGs may not be of much help in fog or haze and may not provide the required visual information during hovering or landing in dust or snow.

5. **Automatic gain control (AGC)**— The AGC adapts the brightness of the screen to changes in ambient illumination levels and to protect the electron multiplier from extensive firing when exposed to strong light. In first- and second-generation NVGs, bright light sources such as car headlights or flares, create a halo or "blooming" around the bright light and degraded the contrast of adjacent portions of the image. In third-generation tubes, AGC balances the brightness level of the whole image, more effectively. However, this also results in a darker image with lower contrast ratios (Verona, 1985). Thus, the presence of even a small source of bright light in the field of view of the NVGs reduces the average brightness of the image and its ability to produce distinct contrasts.

6. **Noise**— The photo cathode randomly emits electrons, which create a constant noise level. When the world image is bright, signal-to-noise ratio is high and noise has little effect on the visual image. When the image is dark, however, the signal-to-noise ratio is lower so the image may be significantly degraded by the noise.

7. **Tube condition**— Light intensifiers have a limited life span. Their performance gradually deteriorates as a function of time and light exposure. Since the tubes may be replaced independently, one may be significantly inferior to the other at any point in time. The differences in brightness between the two images may cause depth and movement illusions such as the Pulfrich pendulum (Rogers and Anstis, 1972). Another possible outcome is that the weaker image may be suppressed, resulting in a monocular rather than a binocular image. Hence, it is very important to avoid this situation by maintaining both tubes at adequate and approximately equal levels of performance.

8. Goggle's mechanical condition— The goggles must be in good mechanical condition. Shaking controls or worn-out joints may cause various optical problems. One common (and usually ignored) defect occurs when the two tubes are not exactly parallel. This may lead to the suppression of the image of one eye, inappropriate distance estimation, and headaches (see also section IV.B-IV.D).

9. Wind shield— A scratched or dirty windshield may significantly reduce night visibility with unaided eyes. The effect may be even more pronounced with NVGs, because of to their enormous sensitivity to the light which may be reflected by the scratches or by dust particles (see also next section).

### D. Cockpit Lighting

The image intensifier multiplies the light that reaches the tube thousands of times. The rate of light intensification depends on its wavelength. Second-generation tubes are reactive to light in the range of 0.35-0.90  $\mu\text{m}$ , with a sensitivity peak around 0.50  $\mu\text{m}$  (fig. 4). Third-generation tubes react in the range of 0.50-0.92  $\mu\text{m}$ , with a peak around 0.85  $\mu\text{m}$ .

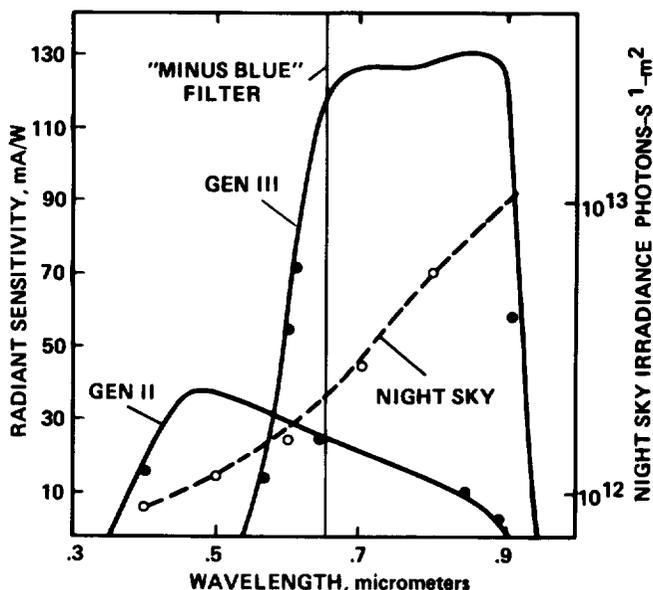


Figure 4.— Wavelength sensitivity of second- and third-generation NVG tubes and the effect of “minus blue” filter.

Most military helicopter crew stations are equipped with red light, which is especially designed to preserve night-vision adaptation (“aviation red”—0.6  $\mu\text{m}$  and above). However, this light also interferes with the NVGs. It causes an automatic gain reduction which results in a poor world image (Breitmaier and Reetz, 1985). Secondary reflections from the windshield which are in the user's direct field of view, may be even worse than the original light sources. Broad-band white light, used in fighter aircraft cockpits, creates similar effects.

The problem may be solved by using short wavelength light. Both generations of tubes are relatively insensitive to blue light in the range below 0.38  $\mu\text{m}$ . However, blue light is ineffective for instrument and

map reading. Hence, a compromise has to be made: using a blue-green or green light which satisfies both the requirements of the pilots' eyes and the NVGs.

The problem is easier to solve with third-generation tubes which have a clear cutoff point below 0.50  $\mu\text{m}$ . In the third-generation ANVIS, a "minus blue" filter, which rejects wavelengths under 0.665  $\mu\text{m}$  is built in (fig. 4). It enables the use of a relatively wide range of blue and green lighting in the cockpit (Verona, 1985). While this filter has little effect on image quality in vegetated areas, it may significantly reduce the contrast levels of desert views. Thus, for desert environments, a lower cutoff point of 0.625  $\mu\text{m}$  is recommended.

The use of homogenous, narrow band, green lighting raises a series of human factor problems:

- a. It is difficult to distinguish colors or even gray shades on maps and aerial photographs.
- b. The use of color coding, such as red warning lights, causes serious problems. With the introduction of multi-purpose CRTs into helicopter cockpits, particularly color displays, the problem may become even more complicated (Genco, 1985).
- c. The sensitivity of the retinal rod system at 0.5  $\mu\text{m}$  (green light) is approximately 5 orders of magnitude higher than at 0.68  $\mu\text{m}$  (red light) (Hood and Finkelstein, 1986, pp. 5.9-5.12). Hence, green light has a stronger detrimental effect on night-vision adaptation than does red light. As long as the pilot uses his NVGs his eyes are not dark adapted and he does not rely on unaided vision. However, aircrew members who do not use goggles, may be effected by the green light and experience deteriorated dark adaptation.

This raises a basic dilemma about the design of future crew station lighting systems. Should each cockpit have dual systems of red and green lighting (resulting in considerable technical problems), or is it sufficient to have only NVG-compatible lighting? Will NVGs prevent the use of multicolor display systems in the future cockpit (or require them to have a monochrome backup mode)? More research is required to determine the operational consequences of reduced dark adaptation due to green light, and the implications of NVG lighting compatibility on the design of advanced crew stations.

### **E. Superimposed Symbology**

Although the ANVIS is designed to enable the user to see the instrument panel with his naked eyes, reading instruments which are different in illumination and optical distance from the world view, is quite difficult (Simmons, Kimball and Hamilton, 1985). When flying at very low altitudes or while hovering in dust or fog, pilots are practically incapable of monitoring flight instruments. Therefore, they must rely heavily on information about aircraft status provided verbally by the copilot. This requires a high level of cooperation and coordination by the flight crew (Haidn, 1985).

Recently, attempts have been made to add flight symbology to NVGs (e.g., Simmons, Kimball, and Hamilton, 1985). Since the intensifier tube does not have video input capabilities, symbology has to be incorporated into the optical path, in front of or behind the tube. One technical solution is to project an image from a miniature CRT onto a semitransparent combiner lens which is installed in front of one of the tubes. Symbology is seen through the NVGs, superimposed on the world view (fig. 5).

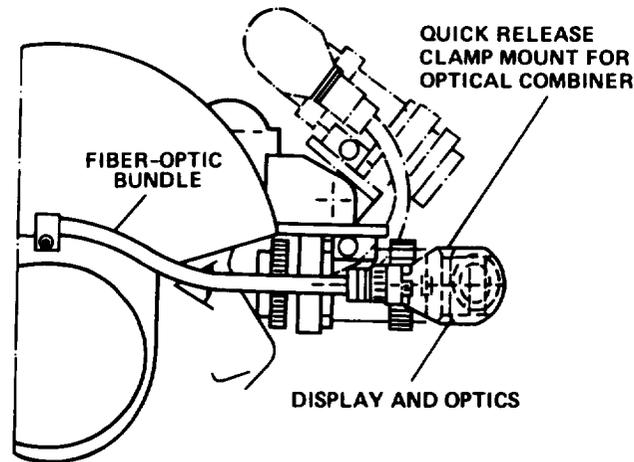


Figure 5.— Side view of NVG symbol generator in active position (solid line) and stowed away (dotted line).

This solution seems to be more feasible than the attempts to display the symbology after the NVGs (between the eyes and the goggles; Simmons, Kimball, and Hamilton, 1985), because it displays the symbology and the world view through the same optical system. It raises however some technical and human factors problems:

- a. The color of the CRT has to be chosen such that it may be seen through the goggles but does not interfere with the world image.
- b. The display has to be bright enough to be legible against various backgrounds. However, the automatic gain control (AGC) does not distinguish between symbology and other sources of light. Therefore, it may adapt the tube to the bright symbols by reducing its sensitivity, resulting in a dark and reduced quality world view.
- c. Further perceptual implications of flight symbology are discussed in section IV.G.

### III. DAY VISION AND NIGHT VISION

The human visual system is the most important source of information during flight. Pilots rely on acute vision to detect remote targets and small obstacles. Depth perception is required to estimate altitude and distance. Peripheral vision enhances velocity estimation, obstacle detection and general orientation. During the day, with good visibility, the pilots' eyes provide a clear and highly detailed image of the environment. At night, the amount of available information is reduced in many different ways (e.g., brightness, contrast ratio, level of detail, color). The use of visual aids, such as NVGs, enhances information for only some of these sources of reduced visibility, but at the expense of degrading other visual functions. Some basic understanding of human day and night vision may be of value for the operator who has to rely on night vision, with or without visual aids.

## A. The Human Eye

The human eye may be compared to a camera containing optical components (lenses) and a light-sensitive screen ("film"). This is a highly sophisticated system which contains two complementary sub-systems (the two eyes) and is capable of adjusting to day and night operation across a range of almost 14 orders of magnitude of light intensity (Hood and Finkelstein, 1986). Figure 6 depicts a schematic cross section through the eye.

Light rays from an external source (sun, moon, artificial light), are selectively reflected by objects in the scene. Part of the light is refracted by the cornea, passes through the pupil and reaches the lens.

1. The pupil is a hole in the center of a radial muscle (the iris). The diameter of the pupil is affected by the level of luminance and is responsible for an important, but relatively small portion of light adaptability.

2. The lens is a flexible transparent body which concentrates light rays on the retina. The lens is relatively flat when viewing distant objects and concave when viewing near objects.

3. The retina is a tissue composed of light sensitive cells, nerve cells, and nerve fibers. It contains two types of receptors, cones and rods:

- a. The cone system operates under moderate to high light intensities. It is responsible for color vision and for the detection of fine detail. The human retina contains approximately 6.5 million cones, a great part of which are concentrated in a small area—the fovea. The cone population is most dense in a  $1.5 - 2.0^\circ$  area and falls rapidly to a minimum by  $10^\circ$  eccentricity (Hood and Finkelstein, 1986; fig. 7). Pure cone mediated vision is called photopic vision and exists in the illumination range of  $10 - 10^8$  millilamberts.
- b. The rod system is more sensitive at low light levels. It is poor at discriminating details and does not provide color discrimination. Approximately 120 million rods are distributed throughout the retina, although there are none in the fovea and in the "blind spot" (fig. 7). Under intense

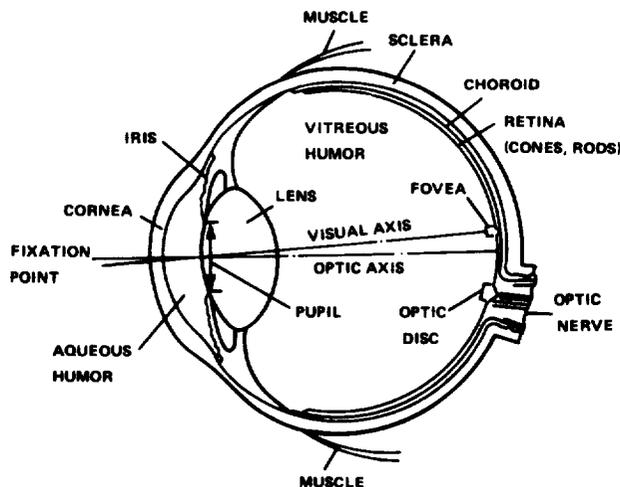


Figure 6.— Cross section of the human eye.

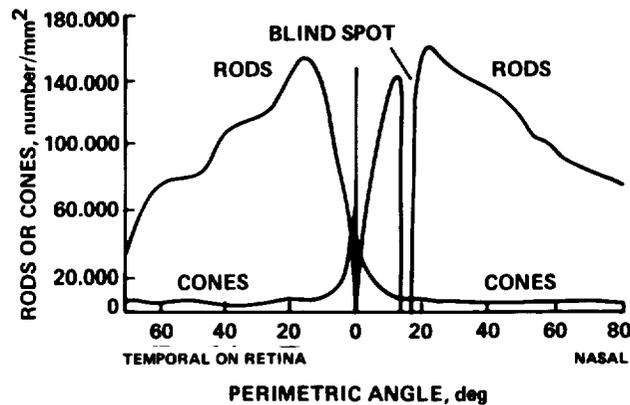


Figure 7.— Rod and cone density as a function of eccentricity along the horizontal meridian.

illumination, the rods lose their sensitivity and do not react to light. When light is faint, sensitivity is regained through a biochemical process. Maximal sensitivity is reached only after 30-40 min of dark adaptation. Exposure to strong light destroys dark adaptation rapidly. Rods are relatively insensitive to red light (above  $0.62 \mu\text{m}$ ; Hood and Finkelstein, 1986), it is, therefore, possible to dark adapt in an illuminated environment with specially designed red-filter goggles. This provides the justification for using red light in aircraft and particularly helicopter cockpits. Pure rod mediated vision exists in the range between  $10^{-3}$  -  $10^{-6}$  millilamberts and is called scotopic vision.

- c. In the “twilight” (e.g., dusk, dawn of full moon), both systems may operate concurrently, each being only partially effective. This mesopic vision exists in the range of  $10^{-2}$  -  $10^0$  millilamberts.
- d. The optic disk (fig. 6) or blind spot (fig. 7) is the spot where all retinal nerve fibers combine into a bundle, (the optic nerve) which transmits visual information to the brain. This spot does not contain any rods or cones and is, thus, blind. During regular binocular vision, the continuity of the visual field is not interrupted because the blind spots of the two eyes do not overlap. It may, however, create an invisible area of approximately  $8^\circ$  near the center of the visual field, if the world is viewed with only one eye, without head or eye movements.

## B. Seeing by Day and by Night

Because of the functional differences between rods and cones, and to their different distributions, viewing habits which are effective during the day may not be adequate at night, and vice versa. During the day, the small number of cones which are evenly distributed in the periphery of the retina, serve to detect large and moving objects. A central area of about  $10^\circ$  provides acute vision. The maximum resolving power of the fovea extends only  $1.5 - 2^\circ$ . To compensate for the small visual field, scanning of the entire scene through rapid eye movements and head movements extends the range of acute vision.

The central area of the retina, which contains only few rods, is practically blind at night. Rod density is highest at approximately  $20^\circ$  eccentricity and declines with further increase in eccentricity (fig. 7).

Hence, effective night-vision has to rely on more peripheral zones of the retina. Staring, which is not recommended during the day, is particularly detrimental for night-vision. Furthermore, rods which have been exposed to light may be easily saturated and temporarily lose their sensitivity. Thus, it is necessary for pilots to scan the scene such that different parts of the retina participate in the scanning process. During twilight, both visual systems may operate together (mesopic vision). At such times, staring may often occur, in an effort to compensate for the low efficiency of foveal vision. However, pilots should avoid this strategy, because it is important to take advantage of both foveal cone vision and peripheral rod vision, to scan the scene, and to avoid staring.

### C. The Use of Night Vision Goggles

The brightness of the NVG display is in the range of 0.3-0.9 footlamberts (second-generation) or 0.7- 2.2 footlamberts (third-generation; Verona, 1975). Image brightness depends on the level of ambient lighting. In a bright scene, the image is relatively bright and when the scene is dark, the NVG image is less bright. The whole range of NVG image brightness is in the medium or high mesopic region where both day and night visual systems operate concurrently (Price and McLean, 1985). However, despite the fact that the rod system is partially operating, the pilots' eyes are not fully dark adapted, thus the efficiency of peripheral vision to monitor the dark outside world, is reduced. The pilots' peripheral, see-around capability (see section II.B and fig. 2) can be used to observe illuminated objects such as flight instruments or maps. And, most important, pilots are capable of perceiving the contour lines of the cockpit and the windshield, to preserve spatial orientation.

After taking the goggles off, approximately 2 min are required to regain full night adaptation (Price and McLean, 1985). For a while, the world may seem "pinkish." This is a chromatic afterimage resulting from the long exposure to green light (the color of the phosphor).

### D. Night Myopia and Instrument Myopia

Pilots are usually required to have at least 20/20 visual acuity, although corrected vision is acceptable in some cases. Surprisingly, national aviation regulations in most western countries (e.g., FAA, US Air Force, German civil aviation, German Bundeswehr, Israel Air Force; Draeger, Hanke, and Wirt, 1985), do not impose any standards for night-vision ability. However, a significant percentage of people with perfectly normal day vision, suffer from night myopia (Sloan, 1947). In general, night-vision standards are not nearly as well-established as are day vision standards. Night-vision is much more difficult to define and measure than day vision because it is highly dependent on the level of dark adaptation, illumination levels, and the presence of dazzling light sources. Some pilots are not aware that their night-vision is deficient or choose to ignore it. It has been found (Wagner and Davidson, 1987) that the use of correcting glasses during night flights only, may minimize the problem of night myopia in some cases.

People who suffer from instrument myopia require optical correction when viewing through optical instruments (Hennesy, 1975). It is quite common for a pilot with normal day vision to choose a negative diopter setting (to compensate for short-sightedness) for their NVGs. This may have some negative implications:

- a. Some pilots may not be aware of their night-vision or instrument-vision capabilities. The quality of an NVG image depend on many variables, therefore, it may be difficult for a pilot to decide whether the image he is watching is optimal.

- b. The optical correction of myopia, particularly over correction and unbalanced correction of the two eyes, may increase misperception of the size, distance, and slopes of objects in the visual scene. (see section IV.D).
- c. Unlike the ANVIS, some NVGs, such as the cat's eyes, may not be equipped with built-in diopter adaptation. Therefore, when using "cat's eyes," the pilots may have to use glasses or contact lenses to correct their vision. However, pilots with normal day vision may not have glasses and may be unaware of the advantages of optical correction at night.

## **IV. SEEING THROUGH NIGHT VISION GOGGLES**

The NVGs provide pilots with a bright "window" in a dark environment which gives them an important operational advantage and enhances flight safety. One should keep in mind, however, that NVGs do not turn night into day. The world image provided by NVGs has many limitations in comparison with normal daytime visibility. This section discusses some of the visual and perceptual characteristics of NVGs.

### **A. Field of View**

Despite the "see around" capability, provided by contemporary NVGs, pilots' effective field of view is considerably reduced in comparison to unaided vision. The ANVIS has a round 40° field of view (FOV), while the "cat's eyes" provides only a 30° field of view. Peripheral vision may provide important cues from the illuminated cockpit environment, but outside peripheral vision is practically eliminated because pilots' eyes are not dark adapted.

In visual flight, pilots depend on peripheral motion cues to estimate speed, altitude, obstacle clearance, and orientation (e.g., Anstis, 1986). In addition, they make extensive use of eye movements to scan the field of view. The natural response to a novel object in the peripheral field, or to an abrupt movement of an object, is a combined movement of both head and eyes toward the object (Hallett, 1986).

NVGs require different, and sometimes unnatural viewing habits. The elimination of peripheral vision and the limited value of eye movements has to be compensated for by constant head movements. Head movements have to be performed slowly and constantly from the center to each side. This rather unnatural behavior has to be acquired during flight training and maintained through practice.

### **B. Binocular Vision**

Most NVGs have two parallel optical paths with two light intensifiers. Each eye is provided with a slightly displaced image, creating binocular vision. In spite of this, pilots report that the world viewed through NVGs appears to be "flatter" than a direct view (Brickner, Wagner, and Gopher, 1987; Department of the Army, Field Manual, 1983). Severe problems may occur if, for some technical reason, the two optical axes are not parallel:

- a. If the optical axes converge, the eyes may converge in the same direction, as though they were viewing a near object (fig. 8a). As a result, under-estimation of size and distance may occur.
- b. In contrast with convergence which is a natural mechanism for viewing near objects, horizontal and vertical divergence are not required in normal vision (fig. 8b). Thus, the eyes have very limited ability to compensate for divergence of the optical axes. As little as 1-2 milliradians of divergence may cause visual fatigue, eye strain, headaches, and even double vision (Warren et al., 1984). Some users may cope with this stressful situation by deliberately or unconsciously suppressing one of the images, thereby losing all binocular depth cues and much of their contrast sensitivity.

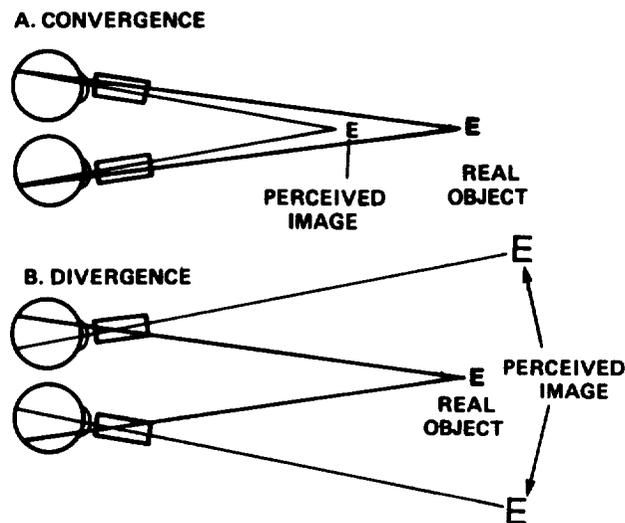


Figure 8.— The effect of convergence and divergence of the optical axes. Convergence may result in size/distance underestimation, while divergence may lead to double vision.

### C. Focal Distance

In the second-generation AN/PVS-5 NVGs, peripheral vision is totally occluded. In addition to the problems created by the lack of peripheral vision, there is a problem of focal distance. Whereas the world view requires a distant focus (“infinity”), instrument, map and chart reading demands a near focus. Some of the technical solutions which have been suggested are:

- a. Manual adjustment of the distance of the field lens; requires pilots to re-adapt the goggles every time they want to read an instrument.
- b. Using bifocal field lenses.
- c. Modifying the NVGs to provide unaided look-under and look-to-the-side capabilities (Price and McLean, 1985).

The last solution is the only one that is effective and has gained pilot acceptance. In the more advanced NVGs, such as the helmet-mounted ANVIS, optical distance is usually maintained at “infinity” to provide a clear view of the outside world. Instruments are read with unaided vision, by glancing beneath the goggles. Shifting from an outside view to the instrument panel and vice versa is a time consuming process. It takes about 1 sec to adapt the focal distance from infinity to a near point or vice versa (Westheimer, 1986). Thus, the total time which is normally required during day flights, to glance into the cockpit, read an instrument, and return to the outside world, is approximately 3-5 sec—a substantial interval of time during low-level flight. When this process has to be performed during NVG flight, it may take even longer because of the unnatural angle of gaze and to possible brightness differences between the NVG image and the instrument panel.

#### D. Vision and Perception

Vision and perception through NVGs involve some unique phenomena, that result from the characteristics of the system.

1. Image quality and brightness— The brightness of the image depends on the level of ambient illumination (e.g., moon, cloud cover) and cannot be controlled by the user. When the scene is bright, the dynamic range of available gray shades is large and the image provides more details, an improved signal-to-noise-ratio and better contrasts than a dark scene. Image quality is also highly susceptible to rain, fog, mist and dust.

Wiley and Holly (1976) compared contrast sensitivity with second-generation tubes to the unaided eye at four luminance levels. At the equivalent illumination of full moonlight, the eye did better than the NVGs at high spatial frequencies (above 8 cycles/deg). NVGs performed better at medium and low frequencies. At lower levels of illumination, NVGs performed better at all frequencies. These results are related to the limited visual acuity which can be achieved with NVGs (see sections II.C1-C2). Thus, NVGs may be very helpful in detecting relatively big objects (e.g., trees, vehicles); however, they are not efficient for detecting very small targets or obstacles (such as wires) and at full moon light, may even be inferior in this respect to the unaided eye.

The spectral sensitivity of third-generation tubes is much higher than the sensitivity of second-generation tubes and their range makes more efficient use of the illumination present in the night sky (see fig. 4 in section II.D). Hence, third-generation tubes may be used effectively in lower lighting conditions. One should keep in mind however, that third-generation NVG tubes have essentially the same resolution limits as second-generation tubes. This means that the unaided eye (provided sufficient illumination) is capable of resolving spatial frequencies which are up to six times higher than those provided by NVGs at their optimal operating range.

2. The terrain— The higher the level of detail and contrast ratios in the scene, the easier it is to interpret the image. For example, the visible texture of a surface provides information for the relative size of objects, their distance shape and slant (Gibson, 1950). Pilots experience greater orientation and navigation difficulties in the desert than while flying over vegetated mountain areas. This is generally true during any night flight but is further pronounced by NVGs due to the limited quality of the image. The high sensitivity of the tubes to red-band illumination emitted by vegetation, as opposed to their lower sensitivity to the green-blue band which is typical of bare desert terrain (Wolfe and Zissis, 1985), further contributes to the problem. The problem may be further amplified by the use of a “minus blue” filter on third-generation tubes (see also section II.D).

3. Distance estimation— Both ANVIS and “cat’s eyes” provide a 1:1 world image. Nevertheless, NVG users tend to overestimate distances. Objects are perceived as being further away (or smaller) than they really are (Brickner, Wagner, and Gopher, 1987). The potential danger of such misperceptions at low level flight, or during landing can easily be imagined.

These misperceptions seems to be related to the phenomenon of “instrument myopia” (see also section III.D). Although the image is projected to optical infinity, the observer tends to focus his eyes to a closer distance (Roscoe, 1985). Hence, the feedback that the brain receives from the eyes’ lens, “tells” it that the observed image is closer than it really is. However, since the angular projection of objects on the retina corresponds with their real distance, they are interpreted as being smaller or further than they really are. In other words, the retinal image of an object which is perceived as remote, is interpreted as representing a big object, while an identical retinal image of an object which is perceived as being close, is interpreted as representing a small object. This relation is known as “Emmert’s law” or the “size-distance invariance hypothesis” (e.g., Epstein 1965).

The use of a negative diopter for the goggles to compensate myopia, reduces the size of the image below its original 1:1 ratio. This may further amplify distance underestimation. Additional problems may occur if the optical paths of the two tube are not exactly parallel (see also section IV.B).

## E. Slope Estimation

Gibson and Cornsweet (1952) defined three frames of reference with which slant can be estimated. It can be estimated relative to: 1) the line of regard (optical slant); 2) some environmental frame of reference such as the horizon (geographical slant); 3) and some adjacent surface or object (relative slant). Two phenomena related to incorrect judgment of slopes have been reported by pilots (Brickner, Wagner, and Gopher, 1987).

1. The gradient of near slopes are often underestimated by the pilot, particularly during approach to landing (Brickner, Wagner, and Gopher, 1987). It is obvious that pilots can not rely on “optical slant,” due to their constantly changing spatial orientation. During approach to landing the pilot must concentrate most of his visual attention in the landing area. Considering the restricted field of view, this would most often leave the pilot with only relative cues for slant estimation. However, because of the limited resolution and contrast ratios provided by NVGs, the visible texture on available reference surfaces is also poor and their slant may be misperceived as well (Gibson, 1950). Accurate slope estimation is essential during low-level flight, particularly when selecting a landing area. If the selected landing area is sloped, there is a risk that the helicopter may roll over or the tail rotor may hit the ground upon landing.

2. The inclination and slopes of distant elements in the scene may also be misperceived. It may be difficult for pilots to distinguish elevations from depressions and to estimate gradients. The tendency is particularly pronounced in desert areas where there is limited terrain texture and a large variety of unpredictable shapes. During good visibility conditions, a pilot would rely predominantly on “geographical” slant cues to estimate distant slopes (e.g., the horizon or a large flat area). However, NVGs limited field of view may reduce the availability of such reference areas in the immediate field of view. Limited resolution and contrast ratios may reduce the usefulness of those surfaces which are visible. These difficulties may be particularly pronounced under marginal lighting conditions.

A distorted representation of the world may lead to disorientation and vertigo. It should be emphasized, however, that the incidence of vertigo is much lower during NVG flights than it is during unaided night flights. The improved world view provided by NVGs enhances object recognition, while general spatial orientation is maintained by looking around them.

### F. Instability of the World Image

Pilots report that they occasionally sense apparent movement in the world image during NVG flights (Brickner, Wagner, and Gopher, 1987); the world appears to be moving when it is, in fact, stable. This illusion is particularly enhanced by sudden or rapid head movements. The illusion may occur as a result of the distance between the eye and the phosphor screen of the intensifier tube. When an unaided eye watches a moving object, relative movement is induced on the retina. When the eyes move and the world is stable, the same relative movement occurs, however, the brain knows how to distinguish between the two types of movements and interpret them correctly (Anstis, 1986).

While wearing NVGS, if a pilot moves his head, the world image moves as described above. Now however, the image is not projected directly onto the retina. Rather it is projected onto the phosphor screen of the intensifier tube, which is approximately 4 in. in front of the retina, and only then onto the retina. Because of the longer radius of movement, the rate of movement on the phosphor screen is higher than would be expected by a natural retinal image (fig. 9). Thus, a pilot may perceive that a stationary object is moving in a direction opposite to the head movement.

To overcome this effect, the pilot has to learn to perform slow, controlled head movements from the center to each side and, whenever possible, to avoid abrupt, rapid movements.

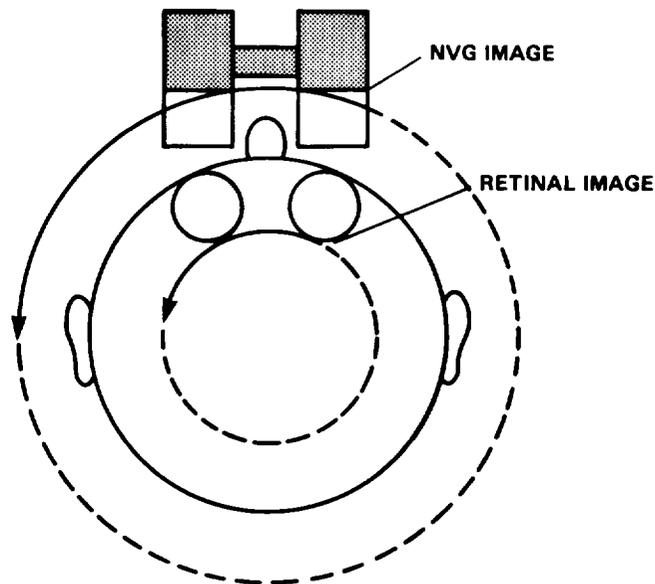


Figure 9.— Schematic description of image motion on the retina and on the NVG tubes. When the head is turned 90° to the right, images on the NVGs move along the large outer circle, while retinal images are expected to move along the small inner circle.

## **G. Brightness and Dazzling**

In first and second-generation tubes, source of bright light such as city lights, car headlights, flares, or the direct view of the moon, create a "blooming" effect. This reduces the quality of the whole image and can be very disturbing (Bohm, 1985). Third-generation tubes have a more efficient AGC, which adapts the average brightness of the whole image to the momentary level of illumination. Thus, the disturbing effect of blooming is much less of a problem. However, the AGC reaction to bright light also reduces the total brightness of the screen and its dynamic range of gray shades (which is low to begin with because of the low peak brightness of NVG displays). Hence, whenever possible, a pilot should avoid looking directly at bright sources of lighting.

## **H. Monochrome Images**

The color of the image is determined by the type of phosphor used on the screen. Most contemporary NVGs use fast-response green or yellow-green phosphors (e.g., P-20). The system generates a monochrome image in which the "gray shades" are actually various intensities of green. In fact, unaided night-vision is monochrome as well, because the rods are insensitive to color differences. However, there are various sources of information in the outside world and particularly within the cockpit, in which color plays a vital role. Inside the cockpit, warning lights have to be modified or eliminated, to maintain NVG compatibility (Breitmaier and Reetz, 1985; see also section II.D).

Colored sections on instruments and on maps may be seen with the unaided eyes. However, since NVG-compatible lighting is narrow-band and homogenous, it is very difficult to distinguish among different hues. Thus, pilots must learn not to rely on color vision. It is essential that all important information in the cockpit has redundant coding so that it may be acquired without relying on color vision. In addition, maps, aerial photographs, and other information charts, must be adapted to NVGs lighting such that different hues also create distinct brightness levels so that they may be distinguished from each other.

Outside the cockpit, obstruction lights and aircraft navigation, anticollision or formation lights carry crucial color information. Sources of red lighting may pose additional problems; because of the extreme red-band sensitivity of NVGs, small or remote sources of red light may seem much brighter than they really are, resulting in poor distance estimations. Since it is impossible to create an "NVG compatible world" outside the cockpit, pilots must be highly aware of the nature of the visual aids they are using and interpret the information it provides accordingly.

The monochrome image provided by NVGs and its range of wavelength sensitivity are inherent characteristics of the system and are not expected to change in the near future. Thus, as long as NVGs are used for helicopter operations, pilots will have to adapt to their limitations and learn to compensate for their modified and sometimes misleading representation of the world.

## **I. Symbology in NVGs**

In spite of the fact that current-technology, helmet-mounted NVGs provide "see around" capabilities, reading panel mounted displays is time consuming and imposes additional workload. During low-level flight and hover it is particularly important for the pilot to keep his eyes outside the cockpit. (Simmons et al., 1985). Thus the pilot is not capable of concurrently reading flight instruments. The problem may be partially solved by superimposing synthetic flight symbology on the world image (fig. 10). The

technical aspects of this possibility have been discussed in section II.E. Although superimposed flight symbology may reduce pilot workload it also involves some potential human factors problems of which both the designer and the user should be aware.

1. **Brightness**– If the symbology is seen through the goggles (as depicted in fig. 5 in section II.E) and if it is too bright, it may drive the automatic brightness control to reduce the brightness of the whole image, thus reducing its quality.

2. **Binocular Rivalry**– The symbols are presented to one eye only, (usually the right eye which is the dominant eye in approximately 70% of the population; Porac and Coren, 1981). This may cause differences in the average brightness level of the two images, and induce different levels of dark adaptation. The eye which receives the darker display has longer reaction times than the other eye. The differences in reaction time may cause illusions of motion in depth like the Pulfrich pendulum illusion (Rogers and Anstis, 1972). In addition, the differences between the images may interfere with the fusion of the two images into one coherent binocular image, and enhance binocular rivalry (e.g., Arditi, 1986). If the symbols are presented to the dominant eye, the user may suppress the other eye without awareness and attribute the poor quality of the image to other causes. If the nondominant eye views the symbols, the user may alternate from one eye to the other, watching each of the images separately. In either case, the user would lose part of his field of view, some contrast sensitivity, and all binocular depth cues.

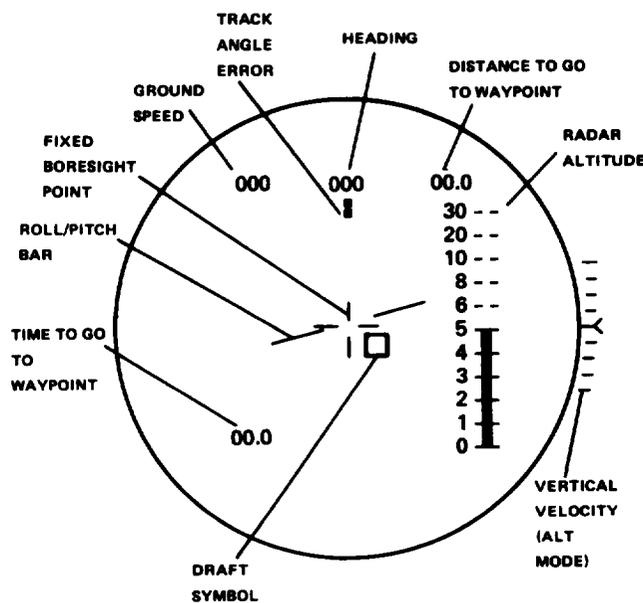


Figure 10.– Example of NVG superimposed symbology.

3. **Focal distance**– Both the world view and the symbology are seen through the same optical system and are, therefore, projected exactly to the same focal distance (“infinity”). However, pilots tend to perceive the symbols as being closer to their eyes than the world view and find it difficult to observe both types of information simultaneously, even though they are superimposed on the same device. The danger is that the pilot might “forget” to look at the world and spent most of the time watching flight symbology,

thereby ignoring obstacles and other crucial information. Similar observations have been made by Apache pilots using a helmet-mounted FLIR display system (Hart and Brickner, in press; also see section V).

4. Symbology distribution— NVGs field of view (40°), is large in comparison with that provided on fighter aircraft and helicopter head-up displays (approximately 20° horizontal) and conventional panel-mounted displays (approximately 10°). It is possible to present all of the symbols at the center part of the display, thus reducing the likelihood that any information might be missed. This solution is also technically simpler because it does not require a wide-field-of-view symbol generation system. Alternatively, the distribution could be across the whole area of the display, minimizing its interference with the central areas of the world image. To optimize the final design, the specific content of information and its importance during various mission phases should be considered. One should bear in mind, however, that NVGs have been designed to present the clearest possible world image. Flight symbology is important and sometimes vital, but it should not interfere with the primary source of information—the world view.

## J. Visual Fatigue

Many pilots report visual fatigue or general fatigue during or after NVG flights. Large individual differences exist, however. Some pilots seem to get tired after as little as 1 hr of flight, while others feel that NVG flight doesn't differ in this respect from flight without goggles on a bright night (Stone, 1984).

Visual fatigue may have some detrimental consequences on performance. For example Schmidt, Abel, Dell'Orso, and Daroff (1979) found that fatigue results in less efficient eye scan patterns. Gregory and Zangwill (1963) found that fatigue increases susceptibility to the autokinetic motion illusion (in which a small source of motionless light is seen as floating in space), a major contributor to disorientation and vertigo.

Although visual fatigue is a well-known experience, it does not have an accurate scientific definition. The main contributors to visual fatigue may be:

1. Physical fatigue— The extra weight that goggles place on the pilot's head, particularly if they are not well-balanced, may cause neck-muscle strain. The required head movements may further enhance the strain. Neck-muscle strain may often lead to a feeling of visual fatigue (Price and McLean, 1985).
2. Physiological contributors— The requirement to monitor continuously an artificial image that emits homogenous, narrow-band light and the constant effort to required spot indistinct targets may cause eye fatigue directly (Stone, 1984). In addition, inappropriate diopter settings (too high, too low, or not balanced), intensifier tubes which are not exactly parallel, external or internal light sources that cause "blooming," and a dark, noisy image may all contribute to or enhance visual fatigue.
3. Psychological factors— Psychological stress and anxiety generally impair performance in many kinds of tasks (e.g., Eysenck, 1982). Mandler (1979) proposed that stress acts as a distractor and demonstrated its effect on reducing working memory capacity. The strain and high workload imposed by low-level flight through a narrow visual window of limited quality, pilot's uncertainty about their ability to detect obstacles, such as wires; and the general stress involved in flying in a dangerous and sometimes hostile environment may involve extra visual strain and create visual fatigue. For example, Pettyjohn (1977) found a high correlation between oxygen consumption and mode of flying; oxygen consumption was highest during NOE flight with NVGs. Pettyjohn interpreted the large differences found between easy and difficult flight modes, as evidence of stress rather than physical effort.

Physical fatigue can be reduced by maintaining general physical fitness, strengthening neck muscles, maintaining an appropriate sitting posture and balancing the NVGs (Department of the Army, Field Manual, 1983). Physiological sources of fatigue can be minimized by good NVG maintenance, selecting optimal settings, and controlling every possible source of interfering light and reflections. Psychological fatigue may be controlled by providing the pilots with all of the knowledge and skills required for the job and by sustaining their level of expertise through regular recurrent training, thus minimizing pilots' workload (e.g., Schneider and Fisk, 1982).

## K. Individual Differences

Pilots' abilities to make efficient use of NVGs, varies significantly. For example, there are individual differences in peoples' abilities to adapt to new visual representations (e.g., Warren and Platt, 1975), learning abilities, susceptibility to illusions and disorientation (Anstis, 1986), focal distance (Leibowitz and Owens, 1975), abilities to detect and identify obstacles and targets, susceptibility to diplopia (double vision) and eye suppression (Warren, Genco, and Connon, 1984), visual fatigue, and the ability to shift back and forth from NVGs to unaided vision (Westheimer, 1986).

Although large interindividual differences, among experienced NVG pilots in visual acuity and contrast sensitivity, have been measured in the laboratory (Price and McLean, 1985), only some pilots are aware of their limited abilities with NVGs. Many pilots experience visual fatigue after relatively short periods of flight and some pilots resent the requirement to use them. To help pilots improve their NVG performance, reduce fatigue or select only those pilots who are likely to succeed in flying with NVGs, it will be necessary to identify the sources of individual differences, devise screening tests sensitive to these factors, and develop improved training methods for those skills that can be improved through training.

Some of the following parameters may be related to NVG ability:

1. Night vision– Night-vision and NVG vision might be correlated, although NVGs are not physiologically the same as “night vision,” but rather mesopic “twilight vision” in which both rods and cones are active to a certain degree (Price and McLean, 1985).

2. Contrast sensitivity– The ability to distinguish adjacent areas of varying contrast ratios is only partially correlated with visual acuity (Ginsburg, 1984). Since pilots vary in their ability to discriminate low-contrast differences with NVGs (Price and McLean, 1985), contrast sensitivity may be a valid predictor of NVG performance.

3. Focal distance– The eyes have a strong tendency to accommodate to a relatively short distance. This tendency is enhanced when viewing an image which is displayed on an instrument, even if the display is optically projected to infinity (Roscoe, 1985; see also sections III.D, IV.C). The NVG world image, is projected to infinity, however, if the eyes have accommodated to a shorter distance, the image will be blurred and objects may appear to be smaller or more distant than they really are (see section IV.C,D). Large individual differences in focal distance, as measured with an empty or a dark field of view, have been reported (Leibowitz and Owens, 1978). For example, Simonelli (1980) found that the dark-focus distance of a population of young flight recruits with perfect visual acuity was 1.19 diopters (84 cm) with a standard deviation of 1.5 diopters (66 cm). Any pilot who tends to accommodate to a near distance may not perform well with NVGs (Roscoe, 1987). However, it may be possible to improve focal distance through biofeedback training methods (Roscoe and Couchman, 1987).

4. Corrected vision— Helicopter pilots in the US Army may have corrected vision. However, the necessity of using eye glasses or contact lenses is determined by tests of day vision only (Price and McLean, 1985). Some pilots with perfect day vision may need correction at night, particularly for myopia (shortsightedness; see section III.D). When using the ANVIS, a pilot may correct his vision either by using his glasses or by adapting the ocular lens of the ANVIS (fig. 2). However, the ANVIS can only compensate for near-sightedness or far-sightedness, while astigmatism has to be corrected by eyeglasses or contact lenses. Some pilots may not be aware of their deficient night-vision or may prefer not to use glasses for other reasons. In addition, Leibowitz and Owens (1978) showed that myopic subjects tend to have a much closer focal distance than do subjects with normal vision. Taken together, problems related to corrected vision (or to vision that requires correction) may significantly limit pilots' abilities to use NVGs adequately.

5. Eye suppression— In approximately 70% of the population, the right eye is dominant (Porac and Coren, 1981). However, this isn't an "all or none" phenomenon. Relative dominance varies along a continuum. One important measure of eye dominance is ocular rivalry. People with strong eye dominance have a stronger tendency to suppress the image of the nondominant eye. Eye suppression may bring about monocular vision which produces a diminished field of view, and reduced contrast sensitivity (Arditi, 1986). Eye suppression is enhanced by differences between the images viewed by the two eyes (e.g., when the tubes have different intensities), and by divergence of the two optical axes (e.g., when the tubes are not properly aligned).

In summary, the "ideal" NVG pilot is one with perfect day and night visual acuity and high-contrast sensitivity, a distant focal point, and well-balanced eye dominance. However, since even the highly selective population of pilots is rarely perfect, it is important to develop methods of diagnosing potential difficulties in NVG flying and to devise appropriate training programs adapted to individual needs. Individual differences must be taken into account: it is particularly dangerous when highly experienced pilots or flight instructors with little insight about the potential difficulties that other pilots may have with NVGs train or lead other pilots who have more limited capacities.

## V. LIGHT INTENSIFIERS VERSUS THERMAL IMAGING

In this section light intensifiers will be compared to thermal imaging (TI) or forward-looking infrared (FLIR) systems. A detailed discussion of human factors in helicopter FLIR systems may be found in Hart and Brickner (in press).

### A. Thermal Imaging Systems

All objects having a temperature greater than absolute zero (0 K or -273°C) emit electromagnetic radiation over a continuous range. The amount of emitted energy depends on the object's temperature and its surface condition, or emissivity. The core of the thermal imaging (TI) system is a sensor (or an array of sensors) which is sensitive to heat or infrared radiation in the 3-5  $\mu\text{m}$  or 8-14  $\mu\text{m}$  band. The sensor scans a given area (through an optical system and a scanner) and transforms the detected energy into electrical pulses which are processed, transformed into a video signal, and displayed on a CRT. Thus, the distribution of emitted heat in a scene is presented as an image in the visible band (Lloyd, 1975).

## B. Characteristics of the Thermal Image

Unlike light intensifiers, TI systems do not depend on the ambient light in the environment and may produce a visible image even in total darkness. In addition, they are capable of “seeing” through dust, smoke, and fog (although water vapor absorbs some infrared radiation), and detecting targets through camouflage. These characteristics increase the operational envelope of TI systems beyond the capabilities of the eyes or vision with light intensifiers (Bohm, 1985).

The quality of the thermal image and the effective range of the system, depend on characteristics of different components, the distribution of emitted heat in the scene, and on atmospheric conditions (Lloyd, 1975). Under good viewing conditions, the effective range of FLIR systems is considerably higher than that of NVGs (of similar magnifications); hot targets may be detected from long distances (Bohm, 1985).

The thermal image represents the distribution of emitted heat in the scenery while direct optical images represent the distribution of reflected visible light. Thus, visual displays of thermal image deviate considerably from the same scene viewed by an unaided eye or recorded by a video camera. These unique characteristics may bring about some difficulties in image interpretation (Hart and Brickner, in press).

1. Shading– Typically, direct optical images are illuminated by a single remote source of light (e.g., the sun or the moon) that is reflected by objects in the scenery. Hence, the image includes attached and cast shades which consistently reflect the direction of illumination. This shading is an important source of information in interpreting the three-dimensional structure of the terrain and seeing surface relief (Todd and Mingolla, 1983). In contrast, thermal images are created by emitted heat. Various shades of gray represent different temperatures. Although these may coincide with real shading (e.g., a shaded area may be cooler than an illuminated area), more often, the meaning of bright and dark areas in a TI is significantly different than it is in a video image. Thus, an attempt to apply familiar perceptual rules of thumb to interpret a TI may result in serious errors.

2. Changes over time– The distribution of emitted temperatures changes constantly as a function of time. In general, the environment cools during the night, which results in reduced temperature contrasts. Thus, the night and early morning hours degrade image quality. Prolonged and uniform heating may also reduce thermal contrasts. In addition, the temperatures of specific components in the scene (e.g., vegetation and soil) may “cross over” at certain times, thereby eliminating the contrast between them (Berry et al., 1984).

3. Polarity– The TI may represent hot areas as light shades (“white hot”) and cool areas as darker shades or vice versa (“black hot”), depending on the option selected by the pilot. Either polarity may seem to be more natural in different situations. For example, the sky is always cold and is usually perceived as a bright area in the image. However if white represents cold, then shaded area which are also cooler will also be bright, in contrast with their natural appearance.

4. Gain and level– At any given moment, the TI system displays only part of the thermal variability in the scenery (Biesel and Rohlfing, 1986). Gain and level controls determine the range of detected thermal contrasts represented on the CRT. The selected condition has a crucial effect on the content of the image. For example, if a large range of gray shades is selected to represent thermal variations within a hot target, only a few gray shades may remain to represent the background.

5. Heat sources— Heat-producing objects, such as vehicles, have a unique “thermal signature.” For example, a tank may have a hot spot at the engine (in fact the engine may be seen through the body of the tank), at the treads (friction heat), and at the cannon (if it has fired lately). Thus, the thermal appearance of the tank deviates significantly from its familiar optical appearance.

### C. FLIR Helicopter Flying

Recently, FLIR systems have been installed in many military and some civilian helicopters to enable night flights and target detection and acquisition through the TI. The most advanced operational system is the one installed in the AH-64 (Apache); the pilot night vision system (PNVS).

The PNVS is based on a turret-mounted FLIR located on the nose of the helicopter, 3.5 m in front and 1.2 m below the pilot’s eye position (fig. 11). The FLIR is slaved to the position of the pilot’s helmet, allowing the pilot to move the 30 (vertical) by 40° (horizontal) instantaneous field of view through a “field of regard” of  $\pm 90^\circ$  azimuth,  $20^\circ$  elevation, and  $45^\circ$  depression. The infrared sensor consists of an array of 180 detectors which provides 360 lines of resolution. This information is transformed into a 875-line video image which is displayed on a 1.92 cm combining lens (a monacle) mounted on the helmet immediately in front of the pilot’s right eye (fig. 12).

### D. Comparison of Thermal Imaging and Light Intensifiers

The following is a concise comparison between TI and NVG as exemplified by the PNVS (the AH-64 TI system) and the ANVIS (third-generation NVG). The comparison relates to general characteristics inherent in the different technologies, as well as to more specific features of the PNVS and the ANVIS, and to the task of flying a helicopter at night.

#### Illumination

PNVS: It does not require ambient illumination and is useful during the day and the night. Depends on thermal variability in the scene.

ANVIS: This requires some ambient illumination at night and cannot be used during the day (it is overly sensitive to bright light).

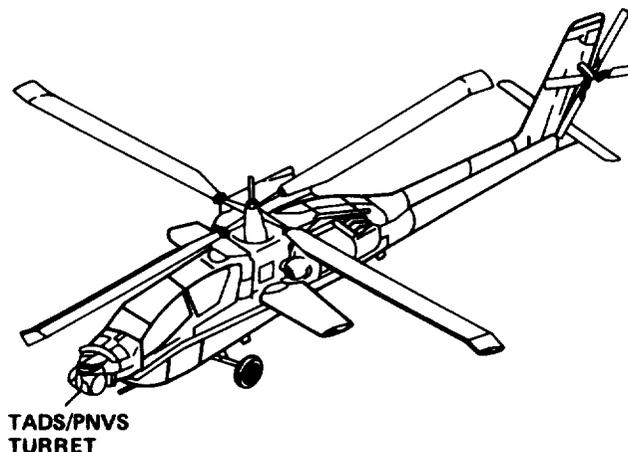


Figure 11.— AH-64 (Apache) with PNVS.

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Figure 12.— PNVS-Pilot's helmet-mounted unit (HMU).

Image brightness

PNVS: User controlled; the maximal brightness is 450 FL. It is sufficiently bright for day and night use and induces photopic vision.

ANVIS: Depends on ambient illumination. The AGC retains brightness in the range of 0.7-2.2 FL and induces mesopic vision.

The nature of the image

PNVS: Unnatural because consistent shading is missing, it is time-dependent, and displays unique "thermal signatures."

ANVIS: Natural because it provides an image that is similar to a black-and-white TV image of the same scene at a higher level of illumination.

### Field of view

PNVS: 40° horizontal by 30° vertical.

ANVIS: 40° diameter, round FOV.

### Field of regard

PNVS: ±90° in azimuth, 20° in elevation and 45° in depression. Field of regard is limited by turret movement capabilities, but is unobstructed within that range.

ANVIS: Field of regard restricted only by head movement limitations and obstructions created by the body of the helicopter.

### See around capabilities

PNVS: The FOV of the right eye practically blocked by HMU (because of brightness differences). The left eye is unobscured.

ANVIS: The central FOV of both eyes blocked by the goggles. Peripheral vision possible, but is restricted by dark adaptation level.

### Degrees of freedom for image movement

PNVS: It has only 2 degrees of freedom, azimuth (yaw) and elevation (pitch). The turreted sensor is indifferent to any other direction of head motion.

ANVIS: The system is helmet mounted, thus the image adapts to head movements in all 6 degrees of freedom.

### Resolution

PNVS: This depends primarily on size and number of sensors, (approximately 360 horizontal lines in PNVS).

ANVIS: Nearly 650 × 650 pixels at the diameter of the image (third-generation tubes).

### Binocular vision

PNVS: None, since the system is monocular. The unaided eye may be used to obtain peripheral cues. However, images from both eyes do not integrate, producing possible binocular rivalry.

ANVIS: Binocular depth perception is induced through two parallel tubes, although pilots report reduced depth cues relative to unaided vision.

### Sensor location

PNVS: Strongly offset from pilot's eye position (3.5 m in front and 1.2 m below pilot's eye). It may invoke apparent motion, parallax, and incorrect distance estimation. The sensor is located outside the cockpit, thus symbology is required to preserve spatial orientation inside the cockpit.

ANVIS: Near pilot's eyes (approximately 10 cm in front). Apparent motion may occur during rapid head movements. The sensor is located inside the cockpit. Spatial orientation is preserved by viewing instrument panel and windshield, through the ANVIS.

### Optical path

PNVS: Indirect. The signal from the sensor is amplified, processed, and transformed into video format.

ANVIS: Direct. The amplified signal is directly transmitted onto a phosphor screen.

### Superimposed symbology

PNVS: Flight and target acquisition symbology are superimposed on the thermal image.

ANVIS: Currently not available. In systems under development symbology may be added by incorporating a display into the optical path.

### Target acquisition

PNVS: The FLIR and weapon systems are slaved to head movements which are monitored by a helmet tracking device. The system provides off-boresight target acquisition capabilities.

ANVIS: Currently not integrated into any weapon or target acquisition system. Head movements are not monitored.

### Range of target detection

PNVS: Two to three times better than ANVIS (at good viewing conditions for both systems), depends on thermal contrasts. Very high for hot targets.

ANVIS: Relatively limited, depends on ambient illumination and contrasts. High for illuminated targets.

### Atmospheric conditions

PNVS: Capable of “seeing” through dust, haze, and smog. Restricted by fog and rain.

ANVIS: Significantly degraded by dust, haze, and fog.

### Environmental requirements

PNVS: To prevent noise, sensor requires intensive cooling (approximately 70 K).

ANVIS: Highly sensitive and has to be protected from intense ambient light. Requires special adjustment of cockpit lighting. Light sources may cause “blooming” and reduce image brightness.

### Training requirements

PNVS: Relatively long; approximately 30 flight hr for an experienced pilot.

ANVIS: Relatively short; 5-10 flight hr for an experienced pilot.

### Weight of head unit

PNVS: Helmet display unit weighs approximately 370 g and is slightly unbalanced laterally.

ANVIS: Weighs approximately 850 g including the battery housing which effectively balances the weight of the goggles.

### Total weight

PNVS: Including sensor, optical components and signal processing units, is very high. Affects power and balance considerations of the whole platform.

ANVIS: Very low (850 g).

### Price

PNVS: Very high, hundred thousands of dollars.

ANVIS: Low, thousands to tens of thousands of dollars.

### Reliability and maintainability

PNVS: Relatively poor, because of system complexity and sophistication.

ANVIS: Very good, because of system simplicity and modularity.

In summary, the PNVS has a considerable operational advantage over the ANVIS: it operates independently of ambient light and has a greater range even under adverse conditions than the ANVIS. Furthermore, the PNVS is a complete, integrated system which provides all of the necessary information for flying as well as target acquisition. The price that has to be paid for these advantages is: a high cost, high weight, significantly more human-factors problems (Hart and Brickner, in press), and longer training requirements, because of the remote location of the PNVS sensor, the monocular display and the nature of the thermal image.

## **E. Combining NVGs and FLIR**

The drive to combine NVGs and FLIR came primarily from the fighter aircraft community. During the last decade, various attempts have been made to use low-light-level TV or NVGs to fly jet fighters at night (Bull, 1985). The main drawback was the limited viewing range of NVGs. Fighter aircraft fly at higher speeds and altitudes than helicopters, and therefore, require longer viewing distances, particularly in the forward direction.

Recently, efforts have been made to develop airborne FLIR systems for fighter aircraft (e.g., LANTIRN, Pathfinder). One of the major issues was where to display the FLIR image; panel-mounted displays are very restricted in field of view (in addition to other obvious disadvantages), whereas helmet-mounted displays have not yet come of age in fighter aircraft. The solution required the development of high brightness, wide field of view, head-up displays (HUD; Warren, Genco, and Connon, 1984). However, on a HUD, only a boresight image of less than  $30 \times 20^\circ$  can be displayed; hence, the combination of a boresight FLIR with the "look around" capabilities of helmet-mounted NVGs seemed to be attractive. Nevertheless, one crucial problem remained: it is impossible to view the FLIR image on the HUD through the NVGs without severe degradation. Thus, the solution required the development of a new type of NVGs. One example of such a system the "Cat's Eyes" (GEC Avionics).

"Cat's eyes" have a combining eye piece that allows direct see through when the NVGs are turned off (fig. 13) and a head tracker. The NVGs are shut off automatically whenever the pilot's head is turned towards the HUD. Thus, the pilot is provided with a continuous "field of regard" which consists of a  $20 \times 30^\circ$  boresight FLIR image with superimposed HUD symbology and a round  $30^\circ$  helmet-mounted,

light intensified image. Whereas this concept is not without its human factors problems (e.g. Cat's eyes have a field of view of only 30° versus 40° for ANVIS, diminished forward visibility through the combiner, NVG shut-off is related to head, but not to eye movements, and different qualities of FLIR and NVG images), successful flight experiments have been reported (Bull, 1985).



Figure 13.– Cat's Eyes night vision goggles.

The idea may be of some interest for helicopters as well, although, off-boresight weapon delivery capabilities (which are integrated into the helmet-mounted PNVS) may be more crucial for helicopters than for fighters.

## VI. CONCLUSIONS

The NVGs, particularly third-generation, helmet-mounted devices, allow pilots to perform NOE flights and other demanding missions under low-visibility conditions. Such missions would be either impossible or extremely hazardous without visual aids. NVGs are relatively cheap, light weight, and simple to operate and maintain. Thus they are a very attractive solution to the requirements for enhanced visual performance at night. However, one has to bear in mind that NVGs do not turn night into day. NVG flights are highly demanding, impose high workload, and require high levels of pilot expertise. The image which is provided by NVGs is different and in many respects degraded in comparison with a direct unaided view of the world under good visibility.

The quality of NVG displays depends on the level of ambient illumination. At very low levels of ambient illumination (e.g., starlight), the image is dark and noisy and provides low contrast ratios. Image quality will vary in different types of terrain and is degraded by atmospheric conditions such as moisture, haze, and dust.

The NVGs provide the pilot with a 40° circular field of view. Because of the bright light emitted by the NVGs, the eyes are not dark adapted. Thus peripheral vision is effective only for the detection of illu-

minated objects, which are primarily inside the cockpit. Pilots must compensate for the relatively small field of view by constant head movements. However, rapid head movements may result in illusions of apparent motion. Despite the binocular vision which is provided by the two parallel NVG tubes, depth perception is often inaccurate; pilots report difficulties in distance and slope estimation.

The ANVIS NVGs provide “see around” capabilities and enable the pilot to monitor panel-mounted flight instruments by looking beneath the goggles; however, this is a time-consuming process. Adding superimposed flight symbology to the NVGs may reduce workload, but may, in turn, create new problems which can affect image quality and enhance undesirable effects such as binocular rivalry and inappropriate accommodation.

It is often assumed that NVG flights are “no problem.” However, the large individual differences which exist among pilots in their ability to make safe and efficient use of NVGs suggests otherwise. Some pilots may adapt to NVGs rapidly and feel comfortable while using them, while others may suffer from excessive visual fatigue and feel uncomfortable even after short periods of flight. All pilots require regular use to sustain their level of expertise (Brickner, Wagner, and Gopher, 1987).

Neither the applied nor basic literatures provides us with sufficient understanding of the psychological and physiological aspects of flight with NVGs. Only small parts of the vast body of vision research literature is related to night-vision and only a fraction deals with mesopic vision which is created by the brightness levels of the NVGs. Individual differences, which are extremely important for the selection and training of NVG operators, have been traditionally ignored by cognitive psychologists and have not been studied systematically. Additional basic and applied research is required to improve our understanding of the human-factors issues involved in night flight in general and in flight with NVGs and other types of visual aids in particular.

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| 16. Abstract<br>Night-vision goggles (NVGs) and, in particular, the advanced, helmet-mounted Aviators Night-Vision-Imaging System (ANVIS) allows helicopter pilots to perform low-level flight at night. It consists of light intensifier tubes which amplify low-intensity ambient illumination (star and moon light) and an optical system which together produce a bright image of the scene. However, these NVGs do not turn night into day, and, while they may often provide significant advantages over unaided night flight, they may also result in visual fatigue, high workload, and safety hazards. These problems reflect both system limitations and human-factors issues. A brief description of the technical characteristics of NVGs and of human night-vision capabilities is followed by a description and analysis of specific perceptual problems which occur with the use of NVGs in flight. Some of the issues addressed include: (1) limitations imposed by a restricted field of view; (2) problems related to binocular rivalry; (3) the consequences of inappropriate focusing of the eye; (4) the effects of ambient illumination levels and of various types of terrain on image quality; (5) difficulties in distance and slope estimation; (6) effects of dazzling; and (7) visual fatigue and superimposed symbology. These issues are described and analyzed in terms of their possible consequences on helicopter pilot performance. The additional influence of individual differences among pilots is emphasized. In the last section thermal imaging systems (forward looking infrared (FLIR)) are described briefly and compared to light intensifier systems (NVGs). Many of the phenomena which are described in the present report are not readily understood. More research is required to better understand the human-factors problems created by the use of NVGs and other night-vision aids, to enhance system design, and to improve training methods and simulation techniques. |  |  |   |   |                  |
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